Bachelor Thesis

Indus3es: Test Rig Calibration and Initial Operation of an Absorption Heat Transformer

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Sworn Statement

I hereby declare that I am the sole author of this thesis and have written it without the help of third parties. Ideas and quotations from other sources that I used directly or indirectly are marked. This thesis has not yet been presented to an examination office and has not yet been published.

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Contents

Nomenclature

Latin Letters

Symbol	Unit	Meaning
c_p	$[J/kgK]$	Specific Heat
$\dot{Q}$	$[kW]$	Heat Flow
R	$[-]$	Düring Factor
T	$[K]$	Temperature
P	$[Bar]$	Pressure
$\Delta\Delta T$	$[K]$	Characteristic Temperature Difference
COP_{th}	$[-]$	Coefficient of Thermal Performance

Greek Letters

Symbol	Unit	Meaning
ν	$[m^3/s]$	Volumetric Flow Rate
ρ	$[kg/m^3]$	Density

Abbreviations

Symbol	Unit	Meaning
AHC	Absorption Heat Converter	
AHP	Absorption Heat Pump	
AHT	Absorption Heat Transformer	
PR	Prototype	
V	Vessel	

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Abstract

The absorption heat transformer is technology known for years, which heats water to high temperature from a heat supply at a medium temperature. This heat supply is usually waste heat coming from a chemical or petrochemical industry which, due to its low temperature, it is not useful any more. Around half of this waste energy can be recovered, so the installation obtains an amount of energy that, otherwise, would be thrown away.

In the Indus3ES project (`http://www.indus3es.eu/`) , the very late developments in heat and mass transfer are used to develop a new absorption heat transformer, taking the absorption heat converter designed in the SEASE project as a reference.

This thesis describes some of the different tasks performed during the assembly of the absorption heat transformer designed by the Institut für Energietechnik of the TU Berlin. With special focus on the installation and calibration of the measuring equipment, as well as an error propagation analysis which determines the precision of the measurements in the prototype, which shows the potential of improvement and different modifications that may be interesting for the following projects performed in the department.

Kurzfassung

Der AbsorptionswÃ¤rmetransformator ist seit Jahren eine Technologie, die aus einer Wärmezufuhr bei mittlerer Temperatur auf hohe Temperatur erwärmt. Diese Wärmeversorgung ist in der Regel Abwärme aus einer chemischen oder petrochemischen Industrie, die aufgrund ihrer niedrigen Temperatur nicht mehr brauchbar ist. Etwa die Hälfte dieser Energie kann zurückgewonnen werden, so dass die Anlage eine Energiemenge erhält, die sonst weggeworfen würde.

Im Projekt Indus3ES werden die sehr späten Entwicklungen in der Wärme- und Stoffübertragung genutzt, um einen neuen Absorptionswärmetransformator zu entwickeln, der den im Projekt SEASE entwickelten Absorptionswärmewandler als Referenz verwendet.

Diese Arbeit beschreibt einige der verschiedenen Aufgaben bei der Montage des vom Institut für Energietechnik der TU Berlin entwickelten Absorptionswärmetransformators. Mit besonderem Fokus auf die Installation und Kalibrierung der Messgeräte sowie eine Fehlerfortpflanzungsanalyse, die die Präzision der Messungen im Prototyp ermittelt, zeigt das Verbesserungspotential und verschiedene Modifikationen auf, die für die nachfolgenden Projekte interessant sein können.

1 Introduction

1.1 Indues3ES Project

The Indus3ES project is an EU funded project for industrial energy and environmental efficiency which follows a previous project, SEASE, where an Absorption Heat Converter (AHC) was designed and developed. This device was a dual mode Absorption machine that could work both as an Absorption Heat Pump (AHP) or Absorption Heat Transformer (AHT).

After this prototype and based on it, an additional prototype has been built. This second design is focused on the AHT mode and it will be tested with 4 different configurations, as it can be seen in Figure 1.1:

1. Prototype 2 (PR2) - Based on the 2015 design, with low (V2) and high (V3) pressure vessels designed by the TU Berlin;

2. Prototype 3 (PR3) - TU Berlin high pressure vessel (V3) combined with Technalia's designed low pressure vessel (V5);

3. Prototype 4 (PR4) - V2 low pressure vessel combined with Technion's high pressure vessel (V4);

4. Prototype 5 (PR5) - V4 Thechion's high pressure vessel combined with V5 Technalia's low pressure vessel.

The project state up to the writing of this thesis is until the end of the assembly of PR2 and before its start-up.

1.2 Theoretical Background

For the following section, information from reference Keith E. Herold, Reinhard Radermacher and Sandford A. Klein (1995) has been used.

Absorption technology

Absorption is a chemical process in which a vapour is transferred into an absorbent. Once the vapour is absorbed into the condensed phase, the absorption heat is released. The result at the outlet is at the condensed state.

Single-Effect Water/Lithium Bromide Heat Transformer (Type II Heat Pump)

The heat transformer, also called as temperature booster or temperature amplifier, is a device that can convert a portion of waste heat energy into useful heat at a higher temperature. It is

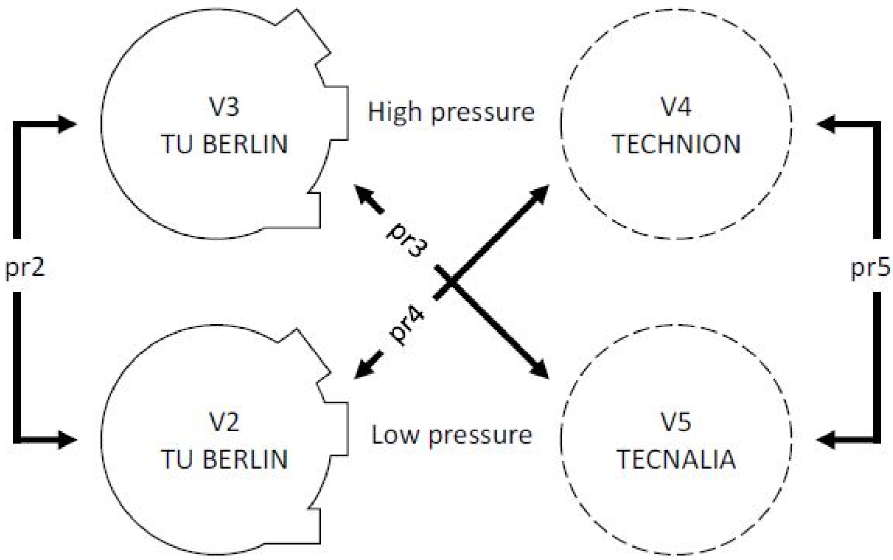

Figure 1.1: *Different configurations to be tested.*

considered in cases where there is an available waste heat and more heat is needed at a higher temperature.

This configuration consists mainly of the following parts:

1. Condenser:
   Water steam coming from the separation of water and LiBr at the Desorber I condensed in the condenser using a cold water source. Then this condensed water is conducted to the Evaporator. There is a recirculation to help the condensation process.

2. Evaporator:
   The Evaporator takes the waste heat, from water at a medium temperature, and uses it to generate steam at the evaporator. This steam is mixed with the concentrated LiBr solution at the Absorber.

3. Absorber:
   The concentrated solution coming from the Generator, and preheated at the heat exchanger, is mixed with the water steam coming from the Evaporator.

   When mixing this two substances heat is released, as this mixture is an exothermic process. This absorption heat is used to heat water to the useful temperature.

4. Desorber/Generator:
   The diluted solution coming from the absorber is heated with the waste heat source.

   As this mixture is an endothermic process, when absorbing the heat from the waste hot water, H2O from the diluted solution is evaporated and separated from the LiBr. This LiBr is concentrated and is then conducted to the Absorber.

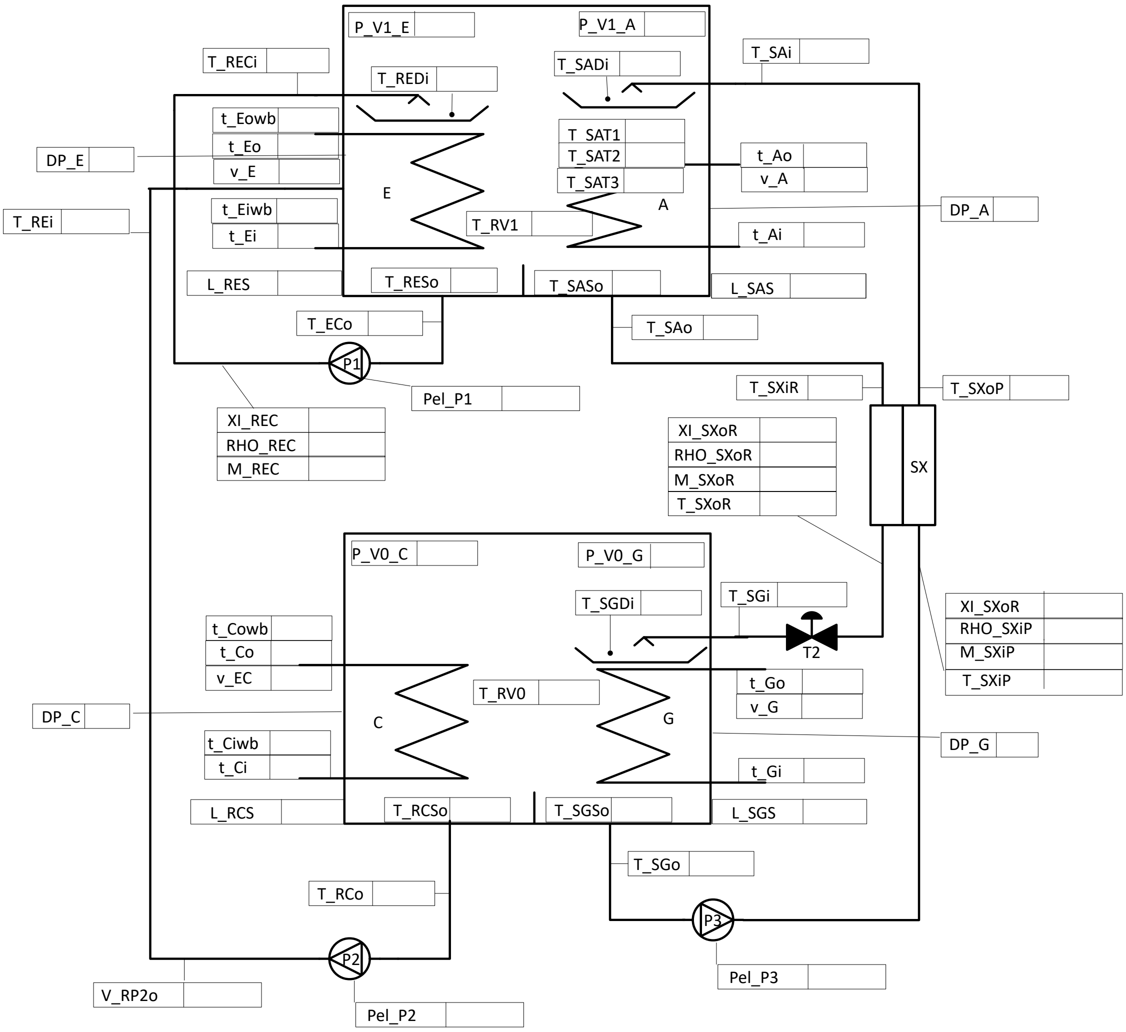

Figure 1.2: *This figure shows the scheme of the heat transformers and the sensors installed in it.*

1.3 Motivation

The waste energy recovery is nowadays an important aspect, not only for the European Union which is trying to lower the environmental impact, but also for the economy of the companies, that can lower the energy costs in their factories.

With the Indus3ES project, the Absorption Heat Transformer (AHT) is studied to obtain higher efficiency rates using the recent advances in the heat and mass transfer technologies.

It is interesting to work in this topic because, besides being able to learn about the absorption technology and the AHT, it can help the European Union to meet its objectives on environmental impact and to become more economically competitive and less dependant on energy imports.

1.4 Scope of tasks

The work in this thesis can be divided in two tasks.In the first part, the work mainly consistedin the assembly of the Indus3ES AHT prototype and the installation and calibration of most of the measuring devices installed to it. This part is described in chapter 2, and details the work performed with the construction of the heat transformer, its tightness tests and the calibration of the temperature sensors.

The second part is a calculation of the performance figures of the absorption heat transformer and a further analysis of the propagation of errors. Taking into account both systematic and standard error, obtained either from the different data sheets or calculated, depending on the characteristics of the parameter of study.

1.5 Organization of the work

The principal methodology used during the length of this thesis was a previous preparation for the task, getting to know with which devices or software were needed before starting working and what results had to be expected. While carrying out the task, document all important information and have an organized register of all that has been done and what is still to do. Finally, once the results are obtained, check if they as expected and document it including any other information useful for future researchers.

2 Assembly and Calibration

In this section, the different tasks performed through this bachelor thesis are described. For each of the tasks the following parts are included:

1. Description of the task
2. Development
3. Results and Discussion

The description of the task explains the main components and tools that are used in the task, as well as an description of the objectives. Then the development is described and finally the results are shown with a discussion and analysis of them, when needed.

2.1 Tightness Tests and Assembly

2.1.1 Description of tasks

For the assembly of the prototype studied in this thesis, all the pipes and connections had to be checked in order to assure its tightness and avoid future problems during its functioning.

In the prototype there are two separate circuits, one for the lithium bromide solution and another for the refrigerant, which is distilled water. In addition, two vessels at different pressure for each of the circuits. A high pressure site, which is around atmospheric pressure and working with evaporation temperatures around 90-100 °C, and a low pressure site, which reaches values of 15-30 mbar approximately and condensation temperatures between 20 and 25 °C.

Due to this characterisctics, tightness is a critical feature of the heat transformer and it has to be proven for values lower to the ones reached in the low pressure site.

Once the tightness of individual sections is proven, the assembly of the different pipes and elements of the circuits takes part. Then the tightness of the whole piping is performed to check the connections to the vessels and to the other elements.

2.1.2 Development

The different sections that form the complete circuit of the heat transformer had to be manufactured in the workshop of the KT building. For this, these sections had to be created from scratch with straight pipes and elbows, connections, accessories for the sensors, etc...

When the stretchs were finished, the Indus3es team proceeded with the testing of the tightness of each of them individually. The process can be summarized in the following list:

1. Pressure test. Looking for the leaks using a mixture of water with soap. When this mixtures is applied on a leak, foam is produced.
2. Vacuum test. Connection of a pressure sensor and a vacuum pump to the section and closing the other ends. With the vacuum pump a partial vacuum is reached, when a pressure value low enough is reached, closing of the connection with the vacuum pump and check how the pressure increases. A maximum leakage rate is defined, when higher values are obtained, leaks on the section have to be sealed.
3. Helium Test. The stretch is connected to the vacuum pump through a device which is capable of detecting helium when it is flowing through it. Using an helium gas bottle with an outlet, which is used to apply helium to the different joints or weldings. If one of this elements has a leak, helium gets in the piping circuit and it is detected by the device described above.

2.1.3 Results and Discussion

In the following table, an example of a solved leak in the prototype is exposed. With this table, the leak rate was calculated and checked, acceptable when lower than $10^{-}3\frac{mbar \cdot liter}{second}$.

The following table shows an example of a non-tight section found in the prototype and later solved. In this case, the section of study included the pump, which its flange was not properly fastened. After checking the flange and fasten it, another test is performed, obtaining acceptable values for the leak rate.

Section	Date	P0	P1	Time	Vol	Leak Rate	State
F to C	01/06/17	0,05	1,66	11	0,65	0,001626	NOT OK.Fasten Flange of Pump
F to C	01/06/17	0,45	1,45	25	0,65	0,000430	OK!

Table 2.1: Example of Leak solving

The columns in the table are:

- Po and P1: initial and final pressure in the section, in mbar
- Time: duration of the tightness test, in minutes
- Vol: volume of the section studied, in liters
- Leak Rate: Rate at which the pressure increases, in $\frac{mbar \cdot liter}{second}$

Most of the leaks found during the tightness tests were located in the welds and connections, due to wrong welding or because of a not proper gasket at the connection. Nevertheless, attention should be paid to the elements of the circuit, such as valves and measuring equipment, and make sure they are correctly installed in the circuit and that the connection between this elements and the circuit is properly fastened and tight.

2.2 Temperature Sensors Calibration

2.2.1 Description of tasks

There are 36 temperature sensors in the test rig of the Indus3es second prototype (PR2).These temperature sensors are resistance thermometers, which work using a precise ceramic resistance, for which an accurate resistance/temperature relationship is known and used to provide the value of the measured temperature.

In order to have a valid and precise value for the different temperatures measured, these sensors need to be calibrated with respect to a reference sensor that the calibrator includes. This reference sensor is calibrated by an external company which assures an absolute value.

2.2.2 Development

Two identical calibration devices have been used to calibrate the 36 sensor. This calibrators were the AMETEK RTC-158-B, as shown in the figure 2.1. The technical specifications can be seen in Annex A.1.

Figure 2.1: *Calibration device used in the Indus3es project*

The following process has been performed to obtain the linear regression parameters that will correct the value of the non calibrated sensors to the real values:

1. Connection of the sensors to the switch board and checking of its right functioning with the Labview tool

2. Connection of the calibrator to the power supply and to the measuring computer via Ethernet connection. For the Ethernet connection, the IP of the computer and the calibrator are set in the same range and both devices are linked. Finally, run the python code to obtain the temperature data from the calibrator

3. Define an appropriate range of temperatures for the sensors to be calibrated and group them together in groups with the same range of temperatures to schedule the calibrations.

4. Set the cycle in the calibrator and introduce the sensors to be calibrated in the calibrator. Chose the right block and isolate them properly. Start the calibration cycle

5. When finished, check that the calibration was successful and get the data from the measuring computer for its later analysis.

6. Read the data with with the python code and run it.
   Thinks to take into account:
   - Correct file and sensor names
   - Time range of the calibration cycle. Starting and finishing time.

7. Calculate the linear regression parameters x1 and x0. Check in the graphical output that the steady state regions are found correctly and there is not any anomaly.

In figure 2.2, a simplified scheme of the calibration circuit is shown:

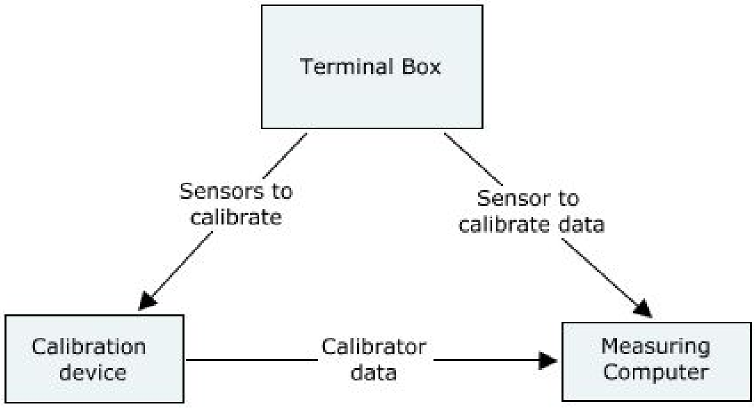

Figure 2.2: *Calibration scheme*

Calibration tool - Python

Then, the values obtained from the calibrator and the sensors to calibrate are processed using a python code written by Lukas Jool, student from the TU Berlin. The function of this code is the following:

1. Recognize and define the Steady-State regions. These are the regions that will be then used to calculate the linear approximation parameters.
   For the steady-state finding, the following parameters have to be defined:

Parameter	Sensor to calibrate	Reference Sensor
minIntervallLength	120	120
IntervallHeadCut	10	10
IntervallTailCut	10	10
maxRelTimeDeviation	10	10
maxDeviation	0,01	0,01
maxMeanDeviation	0,15	0,15
maxDriftRate	0,0001	0,0001

Table 2.2: Steady-State Parameters

This parameters stand for:

- **minIntervallLength**: Maximum length of the interval, in seconds
- **IntervallHeadCut**: Cut at the beginning of the interval, in seconds
- **IntervallTailCut**: Cut at the end of the interval, in seconds
- **maxRelTimeDeviation**: Maximum time difference between two consecutive points of the steady-state, in seconds

- **maxDeviation**: Maximum deviation of a point with respect to the following, in degrees Celsius for our case

- **maxMeanDeviation**: Maximum value of the sum of squares of all the deviations between the points of a steady-state, in degrees Celsius

- **maxDriftRate**: Maximum slope of the interval, derivativ unit

With this parameters, a perfectly flat steady-state region is obtained. As it can be seen in the figures 2.3 and 2.4 attached below.

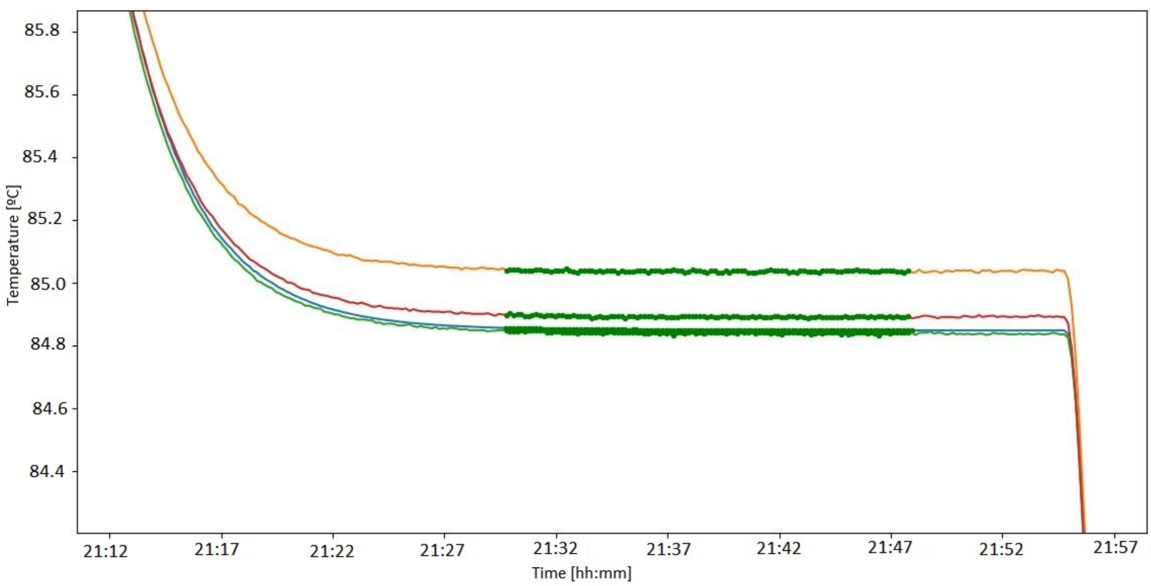

Figure 2.3: *Close look to found steady-state region*

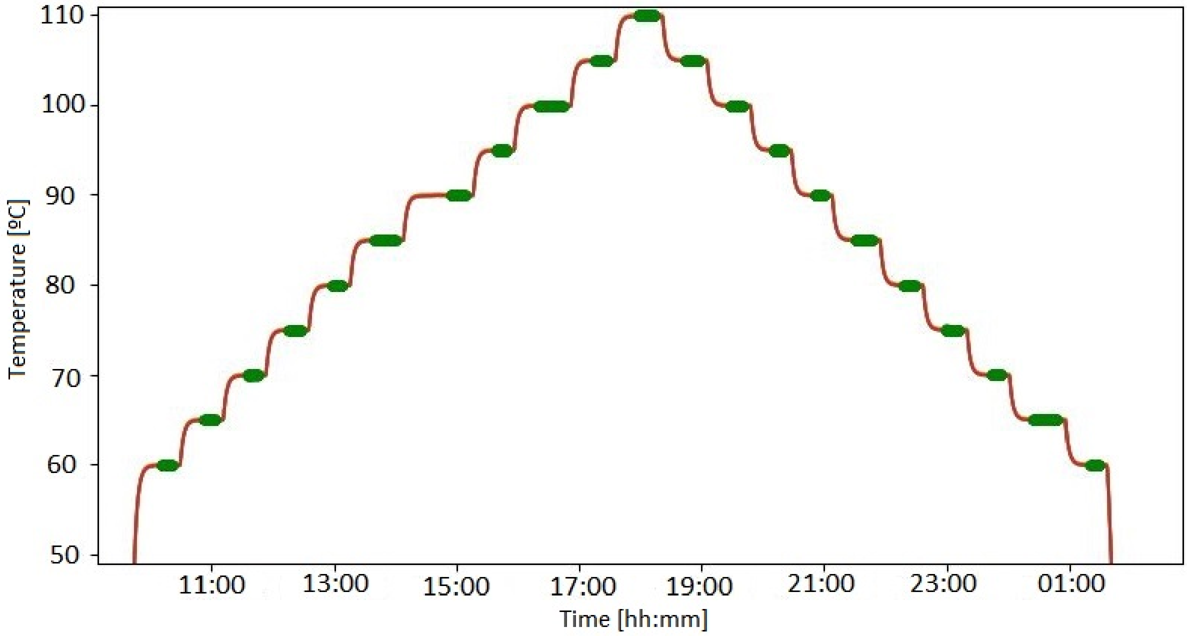

Figure 2.4: *Steady-state regions for a complete calibration cycle.*

2. Calculates a linear approximation using the Polyfit function from pandas library.

3. We obtain the linear approximation parameters that are used to calibrate our sensors.

A complete description of the python script used to calculate the correction parameters for the temperature sensors can be found in Annex B.1 .

2.2.3 Results and Discussion

For the calibration of the temperature sensors, we obtained the linear regression parameters x^1 and x^0 that are used to correct the value that the sensor reads and show a valid value.
All the values obtained are the expected and oscillate between the proper range of values. For x^1 we obtained calibration parameters between 1 ±0.01 and for x^0 between 0 ±0.15.

In figure 2.5 we can see the not calibrated sensors with respect to the reference sensor from the calibrator, before the calibration, the sensors to be installed in the prototype read a slightly different value for the temperature.

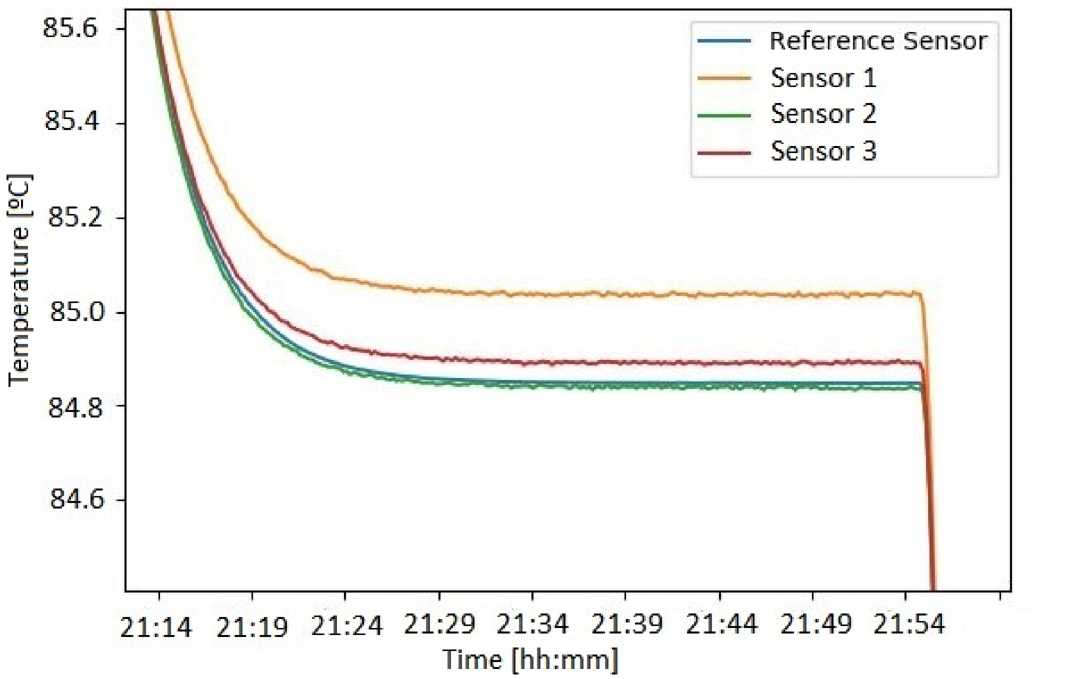

Figure 2.5: *Graphical output from Python script. Sensors to be calibrated and reference sensor.*

And, as we can see in figure 2.6, after the calibration, the sensors are adjusted to the reference one.

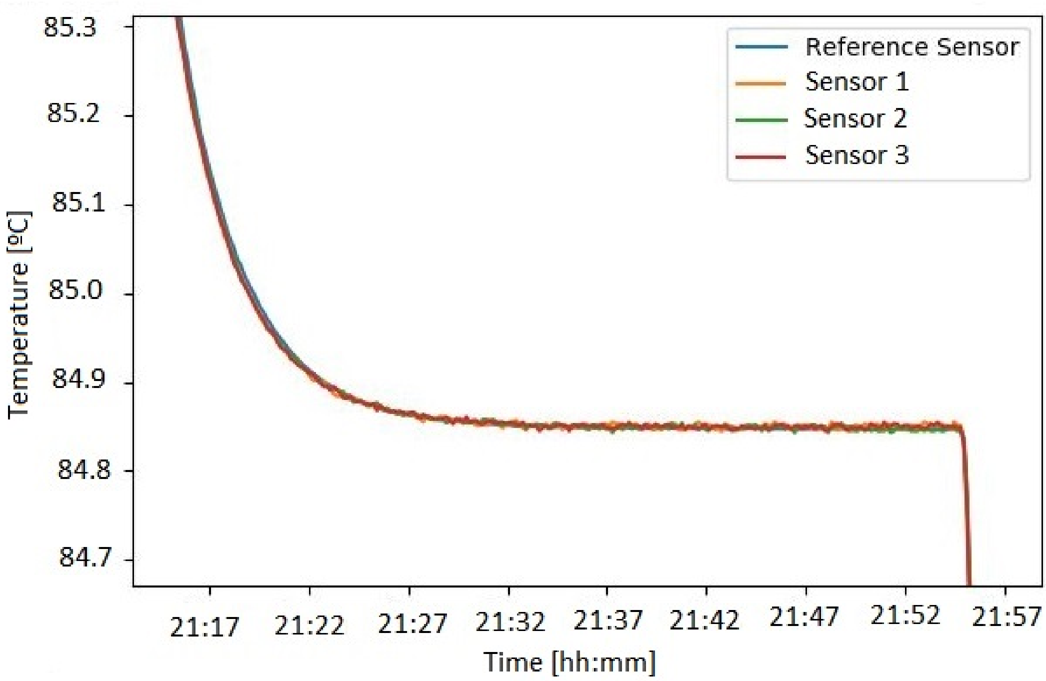

Figure 2.6: *Graphical output from Python script. Sensors after the calibration and reference sensor.*

The results for the different sensors calibrated are shown in table **??**.

Idfr. Nr	**Name**	**Port**	**Temperature Range [°C]**	X^1	X^0
1	T_Sgo	1011	65-110	**0,998**	**0,005**
2	T_SxiP	1012	60/65-110	**0,998**	**-0,087**
3	T_SxoP	1013	80-145	**0,999**	**-0,110**
4	T_Sai	1014	65-110	**0,997**	**-0,031**
5	T_SADi	1015	90-150	**1,003**	**-0,163**
6	T_SAT1	1016	90-150	**0,999**	**-0,053**
7	T_SAT2	1017	90-150	**0,999**	**-0,077**
8	T_SAT3	1018	90-150	**0,999**	**0,003**
9	T_SASo	1019	90-150	**1,004**	**-0,221**
10	T_Sao	1020	65-110	**0,999**	**-0,109**
11	T_SxiR	2013	65-110	**0,999**	**-0,068**
12	T_SxoR	2014	65-110	**0,997**	**-0,056**
13	T_Sgi	3005	60/65-110	**0,999**	**-0,026**
14	T_SGDi	2015	65-110	**0,999**	**-0,066**
15	T_SASo	2016	60/65-110	**1,001**	**-0,110**
16	T_RV0	2017	50-110	**0,999**	**-0,031**
17	T_RCSo	2018	5-55	**0,998**	**0,035**
18	T_Rco	2019	5-45	**0,996**	**-0,005**
19	T_Rei	2020	65-110	**0,997**	**0,076**
20	T_RESo	3009	60-105	**0,999**	**-0,048**
21	T_Reo	3010	60-105	**0,998**	**-0,083**
22	T_RERi	3011	60-105	**0,998**	**-0,044**
23	T_REDi	3012	60-105	**0,999**	**0,023**
24	T_RV1	3013	60-130	**0,999**	**-0,076**
25	t_Gi	3014	60-110	**0,999**	**0,076**
26	t_Go	3015	60-110	**0,999**	**0,034**
27	t_Ai	3016	90-150	**1,000**	**-0,008**
28	t_Ao	3017	90-150	**1,000**	**-0,047**
29	t_Ci	3018	5-45	**0,997**	**0,110**
30	t_Ciwb	3019	5-45	**0,997**	**0,034**
31	t_Co	3020	5-45	**0,998**	**-0,011**
32	t_Cowb	4009	5-45	**0,999**	**0,047**
33	t_Ei	4010	60-105	**1,003**	**-0,085**
34	t_Eiwb	4011	60-105	**0,999**	**0,070**
35	t_Eo	4012	60-105	**1,002**	**-0,026**
36	t_Eeowb	4013	60-105	**0,999**	**0,036**

Table 2.3: Resuls of Temperature Sensors Calibration

2.2.4 Measurement Uncertainty

In order to quantify the influence of the calibration to the error of the temperature sensors, the measurement uncertainty due to the calibration is calculed, following the procedure from reference Lukas Joos (2017).

The approximation used is linear and of first grade, as it can be seen in the following equation:

$$T(T_{KO}, x_1, x_0) = T_{KO} \cdot x_1 + x_0 \tag{2.1}$$

We obtain the uncertainty due to the calibration with:

$$\mu_{Kal}(T) = \sqrt{grad(T) \cdot cov \cdot grad(T)^T} \tag{2.2}$$

Where the gradient from the temperature function is:

$$grad(T) = \begin{bmatrix} x_1 & T_{KO}^1 & T_{KO}^0 \end{bmatrix}.$$

The covariance matrix, which is obtained from the python function that calculates the linear approximation, is the following:

$$cov = \begin{bmatrix} \mu(T_{KO}) & 0 & 0 \\ 0 & \sigma_{x1}^2 & cov_{x1,a0} \\ 0 & cov_{x1,x0} & \sigma_{x0}^2 \end{bmatrix}.$$

And the transported gradient:

$$grad(T) = \begin{bmatrix} x_1 \\ T_{KO}^1 \\ T_{KO}^0 \end{bmatrix}.$$

After developing this, the obtained equality is used to calculate the measurement uncertainty due to the calibration.

$$\mu_{Kal}(T) = \sqrt{x_1^2 \cdot \mu(T_{KO}) + \sigma_{x1}^2 \dot{(}T_{KO}^1)^2 + 2 \cdot cov_{x1,x0} \cdot T_{KO}^1 \cdot T_{KO}^0 + \sigma_{x0}^2 \dot{(}T_{KO}^0)^2} \tag{2.3}$$

Where:

- x_1 and x_0: Slope parameters of linear approximation with calibration.
- $\mu(T_{KO})$: Random Error of the measured value, of the steady state region used to obtain the performance figures.
- T_{KO}: Value of the temperature measurement, for a given steady state, in °C.

After obtaining the uncertainty due to the calibration, we obtain the total error:

$$\mu_{Total}(T) = \sqrt{\mu_{Kal}(T)^2 + \mu_{Sensor}(T)^2} \tag{2.4}$$

Where $\mu_{Sensor}(T)$ is the systematic error of the temperature sensor. And, for a 95,5 %level of uncertainty, we use:

$$\alpha_{95} = T \pm 2 \cdot \mu_{Total}(T) \tag{2.5}$$

The results of the procedure detailed above are shown in section 3.6, with the results of the error propagation analysis.

3 Error Propagation Analysis

In here, the process of error propagation will be described, including all the formulas and the references.

3.1 Errors in measurement

3.1.1 Concepts

This are the two parameters that have to be defined in this error propagation analysis, as it is described in reference C. Babbage and also reference JCGM 100 (2008), referent to the error analysis and its calculation.

- **Systematic Error**: Associated with the faults the equipment may suffer or from a wrong measuring environment
- **Random Error**: Statistical fluctuations (in either direction) in the measured data due to the precision limitations of the measurement device

3.1.2 Random Error

Random Errors are statistical fluctuations in the measured data that happen because of the limitations of the measurement device. As it is said in the reference JCGM 100 (2008) the random error is *the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand.*

For the calculation of the Random Error, also known as standard deviation of the mean, reference C. Babbage has been consulted. First of all, the mean values is obtained:

$$\bar{x} = \frac{1}{N} \cdot \sum_{i=1}^{N} x_i \tag{3.1}$$

Then, the standard deviation:

$$\sigma_x = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{3.2}$$

And, finally, the Random Error or standard deviation of the mean is calculated:

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{N}} \tag{3.3}$$

Where N is the number of measurements of a given steady-state period.

3.1.3 Systematic Error

In most cases, the systematic error is given by the manufacturer. For all the temperature , see annex A.2, and pressure sensors and flow meters, from reference TU Berlin (2016), this value could be found in the data sheets. For the density and Cp values, this parameter had to be calculated with respect to the temperature change, as they are both parameters that are obtained using a function named Coolprop, see reference Bell, Ian H. and Wronski, Jorrit and Quoilin, Sylvain and Lemort, Vincent, which can be run with python or LibreOffice Calc.This process is detailed below.

As Cp or density are a function of temperature, we can make the following statements:

$$C_p = f(T)$$

$$\delta C_p = \frac{\partial C_p}{\partial T} \cdot \delta T$$

And with the following approximation:

$$\frac{\partial C_p}{\partial T} = \frac{\Delta C_p}{\Delta T}$$

The error value can be found with:

$$\delta C_p = \frac{\Delta C_p}{\Delta T} \cdot \delta T$$

And the same for the density:

$$\delta \rho = \frac{\Delta \rho}{\Delta T} \cdot \delta T$$

Where:

- δC_p and $\delta \rho$ are the errors of the specific heat and density, respectively
- ΔC_p and $\Delta \rho$ are the variations of the specific heat and density, respectively

In table 3.1 the systematic error values of all the initial parameters are shown.

Sensor	Systematic Error
Temperature	0,02
Volumetric flow	6E-06
Density	0,143
Specific heat	0,0228

Table 3.1: Systematic Error of the initial parameters

3.1.4 Total Error

In this section, the error propagation formulas for each of the performance figures is obtained. For all the equations shown below, the error used for each of the parameters is the absolute error, taking into account the Systematic and Random Error.

The absolute error is obtained with the following equation:

$$\delta_{abs} = \sqrt{\delta_{syst}^2 + \delta_{rand}^2}$$

For the temperature sensors, which have been calibrated as described in section 2.2, the total error is obtained also taking into account the measurement uncertainty due to the calibration, as this sensors are the only ones in the prototype which have been calibrated. The total error for the temperature sensors is calculated with equation 2.4, which is shown below as a reminder.

$$\mu_{Total}(T) = \sqrt{\mu_{Kal}(T)^2 + \mu_{Sensor}(T)^2}$$

Where $\mu_{Kal}(T)$ is the error relative to the calibration, which already includes the statistical or random error (as seen in equation 2.3), and $\mu_{Sensor}(T)$ is the systematic error given by the manufacturer.

For this, and as it is said in section 2.2.4, equation 2.5, for a 95,5 %level of uncertainty, we use:

$$\alpha_{95} = T \pm 2 \cdot \mu_{Total}(T)$$

3.1.5 Error propagation formulas

First of all, for a given function:

$$R = R\,(X, Y, ...)$$

The general error propagation formula is the following:

$$\delta R = \sqrt{\left(\frac{X}{\partial X} \cdot \delta X\right)^2 + \left(\frac{Y}{\partial Y} \cdot \delta Y\right)^2 + ...}$$

From the formulas described above, we obtain the following cases:

1. Addition or Subtraction
   For:

$$Q = a + b - c$$

   The formula is the following:

$$\delta Q = \sqrt{(\partial a)^2 + (\delta b)^2 + (\delta c)^2} \tag{3.4}$$

2. Multiplication or division
   For:

$$Q = \frac{a \cdot b}{c \cdot d}$$

   The formula is the following:

$$\frac{\delta Q}{|Q|} = \sqrt{\left(\frac{\delta a}{|a|}\right)^2 + \left(\frac{\delta b}{|b|}\right)^2 + \left(\frac{\delta c}{|c|}\right)^2 + \left(\frac{\delta d}{|d|}\right)^2} \tag{3.5}$$

3. Raising to a power
   For:

$$Q = x^n$$

   The formula is:

$$\frac{\delta Q}{|Q|} = |n| \cdot \frac{\delta x}{|x|} \tag{3.6}$$

3.2 Performance Figures

The main performance figures taken from reference TU Berlin (2016) and which error has to be calculated are:

1. Characteristic temperature difference ($\Delta\Delta t$)

2. Heat flow rates

3. Coefficient of thermal performance (COP_{th})

3.2.1 Characteristic Temperature Difference

This parameter can be defined with the following equation:

$$\Delta\Delta t = R \cdot (t_E - t_C) - (t_A - t_G) \tag{3.7}$$

Where:

- R: Dühring Factor, with a value for the LiBr/H2O couple around 1,15
- t_X: External water circuits average temperature at the evaporator(E), condenser(C), absorber(A) and generator(G), in K

3.2.2 Heat Flow Rates

The heat flow rates are calculated in each of the main heat exchangers. In this project, three main flow rates are calculated:

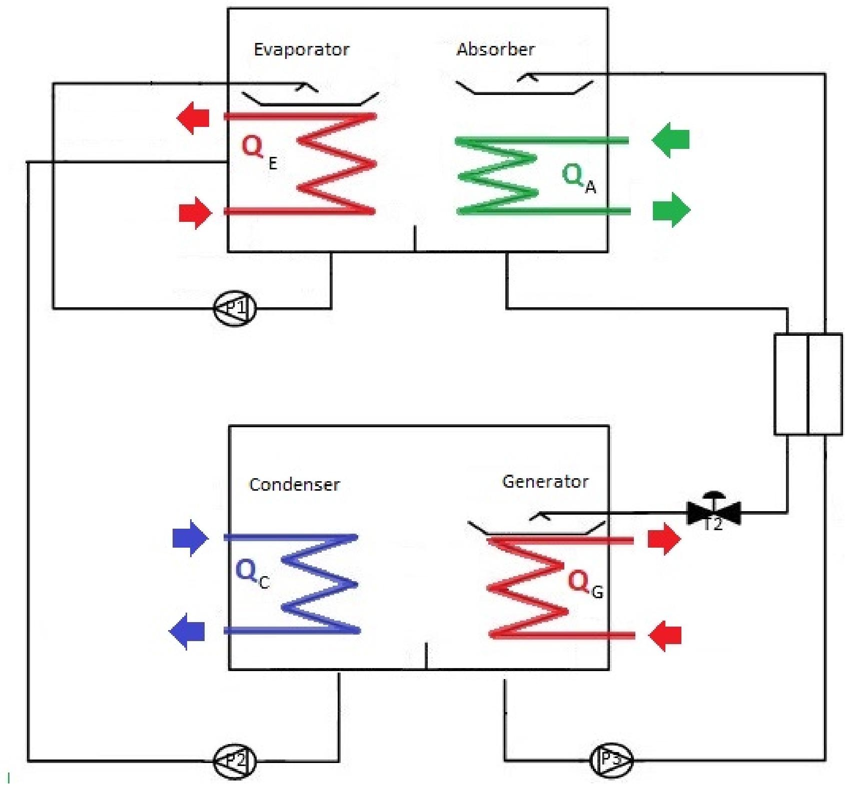

Figure 3.1: *Heat flow rates to be measured in this thesis*

In Figure 3.1, the different flow rates to be calculated are shown:

1. Driving Heat, at the evaporator and generator (in red)
2. Revalued Heat, at the absorber (in green)
3. Cooling heat, at the condenser (in blue)

These flow rates are calculated using the following formula:

$$Q = \nu_{EX} \cdot \rho_{Fluid} \cdot c_{p,Fluid} \cdot (\Delta T) \tag{3.8}$$

Where:

$$\Delta T = t_{Xi} - t_{Xo} \tag{3.9}$$

Being:

- ν_{EX}: Volumetric flow rate, in m^3/s . In the subscript, E stands for external and X can be evaporator(E), condenser(C), absorber(A) or generator(G)
- ρ_{Fluid}: Density of the fluid at constant pressure, in kg/m^3
- $c_{p,Fluid}$: Constant pressure specific heat of the fluid, in J/kg/k
- t_{Xi} and t_{Xo} : Fluid temperature at the inlet and outlet, respectively, in K. In the subscript X can be evaporator(E), condenser(C), absorber(A) or generator(G)

3.2.3 Coefficient of thermal performance

This parameter shows the relation between the useful or revalued heat and the driving heat received by the system in the generator and evaporator.

$$COP_{th} = \frac{Q_{abs}}{Q_{gen} + Q_{eva}} \tag{3.10}$$

Being Q_{abs}, Q_{gen} and Q_{eva} the heat flows in the absorber, generator and evaporator, respectively.

3.3 Total Error Calculation

For the different performance figures exposed in the section above, this is its total or absolute error calculation.

3.3.1 Characteristic Temperature Difference

For the calculation of this parameter, Equation 3.7 is used. Therefore, the error is calculated separating its equation and then adding the error. First, the error for both subtractions is:

$$\delta\left(t_E - t_C\right) = \sqrt{\left(\delta t_E\right)^2 + \left(\delta t_C\right)^2} \tag{3.11}$$

$$\delta\left(t_A - t_G\right) = \sqrt{\left(\delta t_A\right)^2 + \left(\delta t_G\right)^2} \tag{3.12}$$

For the multiplication:

$$\delta R \cdot \left(t_E - t_C\right) = \left|R \cdot \left(t_E - t_C\right)\right| \cdot \sqrt{\left(\frac{\delta R}{|R|}\right)^2 + \left(\frac{\delta\left(t_E - t_C\right)}{\left|\left(t_E - t_C\right)\right|}\right)^2} \tag{3.13}$$

Once the error of each of the parts of the formula is calculated, the error for the characteristic temperature difference is:

$$\delta \Delta\Delta T = \sqrt{\left(\delta R \cdot \left(t_E - t_C\right)\right)^2 + \left(\delta\left(t_A - t_G\right)\right)^2} \tag{3.14}$$

3.3.2 Heat Flow Rates Q

As seen in the Performance Figures, the Heat flow rate is calculated using Formula 3.8. For this calculation, the error is obtained with the following equation:

$$\delta Q = |Q| \cdot \sqrt{\left(\frac{\delta \nu_{EX}}{|\nu_{EX}|}\right)^2 + \left(\frac{\delta \rho_{Fluid}}{|\rho_{Fluid}|}\right)^2 + \left(\frac{\delta c_{p,Fluid}}{|c_{p,Fluid}|}\right)^2 + \left(\frac{\delta \Delta T}{|\Delta T|}\right)^2} \tag{3.15}$$

Where:

$$\delta \Delta T = \sqrt{(\delta t_{Xi})^2 + (\delta t_{Xo})^2} \tag{3.16}$$

3.3.3 Coefficient of thermal performance

As the thermal COP is obtained with Formula 3.10, its error is:

$$\delta COP_{th} = |COP_{th}| \cdot \sqrt{\left(\frac{\delta Q_{abs}}{|Q_{abs}|}\right)^2 + \left(\frac{\delta\left(Q_{gen} + Q_{eva}\right)}{|\left(Q_{gen} + Q_{eva}\right)|}\right)^2} \tag{3.17}$$

Where:

$$\delta\left(Q_{gen} + Q_{eva}\right) = \sqrt{(\delta Q_{gen})^2 + (\delta Q_{eva})^2} \tag{3.18}$$

3.4 Error Analysis Results

3.4.1 1st Steady-State - Highest Heat Flow at the absorber

In the following table, the values for the Random and Systematic Errors for the sensors used to calculate the performance figures are shown:

Sensor	**Average Value**	**Error**			**Units**
		Systematic	Measurement Uncertainty	Total	
t_Ai	129,996	0,020	0,140	0,142	ºC
t_Ao	136,845	0,020	0,112	0,114	ºC
t_Gi	94,999	0,020	0,139	0,140	ºC
t_Go	88,087	0,020	0,138	0,140	ºC
t_Ei	95,239	0,020	0,106	0,108	ºC
t_Eo	87,523	0,020	0,080	0,082	ºC
t_Ci	24,975	0,020	0,161	0,162	ºC
t_Co	32,410	0,020	0,122	0,124	ºC

Table 3.2: Temperature sensors error components, the measurement uncertainty includes the random error

With all the information above, performance figures and its respective errors are calculated, in table 3.4 this results are shown. As it can be seen, this values are between 1 an 4%and can be taken as valid results.

Sensor	Average Value	Error			Units
		Systematic	Random	Total	
v_A	5,000	6E-6	1,4E-3	1,4E-3	m^3/h
v_G	5,000	6E-6	4E-4	4E-4	m^3/h
v_E	5,000	6E-6	8E-4	8E-4	m^3/h
v_C	5,000	6E-6	5E-4	5E-4	m^3/h
Density_A	932,089	0,094	0,003	0,094	$kg/\ m^3$
Density_G	964,437	0,094	0,002	0,094	$kg/\ m^3$
Density_E	964,546	0,094	0,001	0,094	$kg/\ m^3$
Density_C	996,147	0,094	0,001	0,094	$kg/\ m^3$
Cp_A	4267,750	0,150	0,007	0,151	J/kg/K
Cp_G	4206,204	0,150	0,003	0,151	J/kg/K
Cp_E	4206,047	0,150	0,001	0,150	J/kg/K
Cp_C	4179,737	0,150	0,001	0,150	J/kg/K

Table 3.3: Sensor values and associated errors for the higher power output

Performance Figure	Value	Total Error	Units
Characteristic Temperature Difference	30,215	0,286	ºC
Heat Flow Absorber	37,840	1,004	kW
Heat Flow Generator	38,947	1,116	kW
Heat Flow Evaporator	43,477	0,766	kW
Heat Flow Condenser	42,993	1,178	kW
COP Thermal	0,459	0,014	-

Table 3.4: Error values for the higher power output

3.4.2 2nd Steady-State - Highest COP

In the following table, the values for the Random and Systematic Errors for the sensors used to calculate the performance figures are shown:

Sensor	Average Value	Error			Units
		Systematic	Measurement Uncertainty	Total	
t_Ai	129,99	0,020	0,163	0,132	ºC
t_Ao	136,824	0,020	0,130	0,132	ºC
t_Gi	95,014	0,020	0,164	0,166	ºC
t_Go	88,150	0,020	0,161	0,163	ºC
t_Ei	95,064	0,020	0,135	0,136	ºC
t_Eo	87,381	0,020	0,110	0,112	ºC
t_Ci	24,990	0,020	0,187	0,188	ºC
t_Co	32,382	0,020	0,141	0,143	ºC

Table 3.5: Temperature sensors error components, the measurement uncertainty includes the random error

Sensor	Average Value	Error			Units
		Systematic	Random	Total	
v_A	5,000	6E-6	1,4E-3	1,4E-3	m^3/h
v_G	5,000	6E-6	4E-4	4E-4	m^3/h
v_E	5,000	6E-6	1,3E-3	1,3E-3	m^3/h
v_C	5,000	6E-6	6E-4	6E-4	m^3/h
Density_A	932,100	0,109	0,004	0,109	$kg/\ m^3$
Density_G	964,410	0,109	0,003	0,109	$kg/\ m^3$
Density_E	964,654	0,109	0,002	0,109	$kg/\ m^3$
Density_C	996,149	0,109	0,002	0,109	$kg/\ m^3$
Cp_A	4267,725	0,174	0,010	0,174	J/kg/K
Cp_G	4206,242	0,174	0,005	0,174	J/kg/K
Cp_E	4205,894	0,174	0,003	0,174	J/kg/K
Cp_C	4179,738	0,174	0,001	0,174	J/kg/K

Table 3.6: Sensor values and associated errors for the higher COP

In the second steady-state studied, the error values are similar to the first case, explained above. In this case, the errors also take values between a 1 and a 4 %, which are the expected values in this calculation.

Performance Figure	Value	Total Error	Units
Characteristic Temperature Difference	30,090	0,339	ºC
Heat Flow Absorber	37,743	1,165	kW
Heat Flow Generator	38,666	1,308	kW
Heat Flow Evaporator	43,299	0,995	kW
Heat Flow Condenser	42,748	1,364	kW
COP Thermal	0,460	0,017	-

Table 3.7: Error values for the higher COP

3.4.3 3rd Steady-State - Lowest Heat Flow at the absorber

In the following table, the values for the Random and Systematic Errors for the sensors used to calculate the performance figures are shown:

Sensor	Average Value	Error			Units
		Systematic	Measurement Uncertainty	Total	
t_Ai	130,125	0,020	0,108	0,110	ºC
t_Ao	131,189	0,020	0,105	0,107	ºC
t_Gi	85,002	0,020	0,093	0,095	ºC
t_Go	83,815	0,020	0,076	0,079	ºC
t_Ei	85,206	0,020	0,078	0,081	ºC
t_Eo	83,323	0,020	0,065	0,068	ºC
t_Ci	37,997	0,020	0,065	0,068	ºC
t_Co	39,624	0,020	0,066	0,069	ºC

Table 3.8: Temperature sensors error components, the measurement uncertainty includes the random error

For the last steady-state studied, the error or uncertainty values are between 3 and 15%, as shown in table 3.10.

This percentage values are to high in comparison with the two other cases studied above, nevertheless, this steady state is the one which includes lower values for all the performance figures. Due to that, having a similar error value for all three cases, represents a very different percentage of the studied value.

Sensor	Average Value	Error			Units
		Systematic	Random	Total	
v_A	4,200	6E-6	7E-4	7E-4	m^3/h
v_G	5,000	6E-6	4E-4	4E-4	m^3/h
v_E	5,000	6E-6	7E-4	7E-4	m^3/h
v_C	5,000	6E-6	5E-4	5E-4	m^3/h
Density_A	934,461	0,057	0,002	0,057	$kg/\ m^3$
Density_G	969,158	0,057	4E-4	0,057	$kg/\ m^3$
Density_E	969,251	0,057	4E-4	0,057	$kg/\ m^3$
Density_C	992,787	0,057	2E-4	0,057	$kg/\ m^3$
Cp_A	4262,1599	0,091	0,005	0,091	J/kg/K
Cp_G	4199,7950	0,091	5E-4	0,091	J/kg/K
Cp_E	4199,6763	0,091	6E-4	0,091	J/kg/K
Cp_C	4178,9415	0,091	4E-5	0,091	J/kg/K

Table 3.9: Sensor values and associated errors for the lower power output

Performance Figure	Value	Total Error	Units
Characteristic Temperature Difference	6,025	0,214	ºC
Heat Flow Absorber	4,943	0,711	kW
Heat Flow Generator	6,708	0,699	kW
Heat Flow Evaporator	10,646	0,597	kW
Heat Flow Condenser	9,376	0,557	kW
COP Thermal	0,285	0,044	-

Table 3.10: Error values for the lower power output

3.4.4 Comments on the Error Analysis Results

In this section, the results from the error analysis are shown, and have the expected results for both first and second steady-states, but for the third case this values are bigger than expected. This unexpected results obtained in the third case can be caused because the values of the performance figures itself are significantly lower than in the other cases, as all the error values have similar magnitude for all steady-state periods studied.

When calculating this values, it has been observed that the main element or the element that has contributed with a higher percentage to the total error has been the uncertainty due to the measurement or measurement uncertainty. While this thesis has been written, some of the calculations have been repeated due to errors of the author. As an example of this corrections on this document, total errors of the performance figures were first calculated not taking into account the measurement uncertainty, and once the measurement uncertainty was included in the calculation, as it should be done, the total error values increased significantly. This contribution of the measurement uncertainty can be seen in tables 3.2 , 3.5 and 3.8 .

As scientific studies always focus on lowering the uncertainty of its measurements in order to be more precise and obtain more reliable results, a few options to reduce the error will be described. In order to minimize the random error, or statistical contribution to the error, more data should be taken. By increasing the number of measurements of a steady-state period, the random error is reduced. When talking about the systematic error, it is more difficult to reduce and often not economically viable. That means that in order to reduce the magnitude of the systematic errors of the measuring devices, more expensive material has to be used, and usually the difference may not be useful for the project itself.

4 Summary and Lessons learned

This thesis describes the work performed with the Indus3es project and the main tasks developed in the thesis are the assembly of the prototype of the absorption heat transformer, installation and calibration of the temperature sensors and posterior calculation of the performance figures and its error propagation analysis.

Even though the results obtained were as expected, some difficulties appeared when performing the tasks detailed above. As a general advice for further researchers, it is recommended to prepare and inform oneself about the work to be done and the instrumentation that has to be used, in order to accelerate the work and avoid doubts. Also, it is important to have a global view of the project at the beginning of it, in order to perform the works taking into account the future necessities that may appear.

Other specific recommendations referent to each of the sections of this thesis are also interesting for future researchers. In the assembly of the prototype, special attention has to be paid to the communication between the designers of the prototype elements and the manufacturers and welders, to avoid misunderstandings that slow down the process. For the tightness tests, a previous visual inspection of the welded sections can accelerate the detection of leaks, also using the proper gaskets and sealing paste for each connection will shorten the work. When calibrating the sensors, it is necessary to fully understand the python calibration script and to know which parameters will be needed to calculate the propagation of errors, as well as the functioning of the calibration device.

To conclude, the relation between chapter 2 and 3 in this thesis should be pointed out. The calibration of the temperature sensors has given an important contribution to the error propagation, as it can be seen in the result tables, the measurement uncertainty due to the calibration provides approximately a 90%of the total error of the temperature sensors.

5 Outlook and future research

As it can be seen in the sections above, the main objectives of this thesis have been accomplished. First of all with the assembly and installation of the prototype and a posterior error analysis of the performance figures. With both of this tasks, it has been possible to obtain a more general view of the process of building a prototype and test it, and also the important relation in between the building and installation of the sensors which had to be used for the data acquisition and posterior analysis.

The first part of this thesis was more practical than theoretical, more hours were invested on it, due to the workshop work with the assembly and the different related tasks. In this part, the previous preparation was crucial, it was very helpful to get knowledge of the devices to use and fully understand the objectives of each task. With the calibration of the temperature sensors, more precise results would have been obtained by increasing the degree of the approximation polynomial, that would lower the values of he covariance matrix, which much contribute to the total uncertainty of this sensors.

The second part has been more theoretical, with the error analysis of the performance figures. In this section, more attention has been paid on the understanding of the main concepts and the data management in order to work efficiently avoiding any kind of error. In order to improve the precision of the measurements, longer steady-states would decrease the random or statistical error, but to improve the systematic error of the devices a not worthy investment would be necessary.

Finally, and for a further research on this topic, a more complex measurement uncertainty study could be performed on the performance figures and also to create a continuous calculator for this uncertainties and errors. With this continuous control, it would be much easier to study in which conditions of work of the prototype the uncertainty is the lowest, and to determine which are the factors that contribute in a greater or lesser extent to it.

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A Annex A

A.1 Calibrator Technical Data

temperature

JOFRA® calibration

Reference Temperature Calibrator

RTC-158 & RTC-250

Both for liquid bath and dry-block use

Liquid Bath

Dry-Block

» High accuracy

Down to ±0.04°C using the external reference sensor. 4-wire True-Ohm-Measurement technology is used

» Excellent stability 0.01°C

» Wide temperature range

RTC-158 from -22 to 155°C (-8 to 311°F)

RTC-250 from 28 to 250°C (82 to 482°F)

» Excellent temperature homogeneity

Unique active dual-zone block ensures good temperature homogeneity in the calibration zone

Patent pending!

» DLC Dynamic Load Compensation

Perfect temperature uniformity in the insert, even when calibrating large sensors or many sensors at a time.
B and C models only

» Temperature uniformity indicator

Shows the degree of temperature uniformity in the insert when using the new DLC technology.
B and C models only

NEW!

» New sensor basket

In combination with the stirrer the newly developed sensor basket ensures virtually zero axial and radial gradients in the calibration zone

» Intelligent reference sensors

JOFRA reference sensors are supplied with intelligent plugs, holding the calibration data (coefficients) of the reference sensor. This is a truly plug'n'play calibration system

» USB communication

All RTC calibrators communicate via an easy-to-use USB port

» EURAMET

Best performing dry-block with regard to the EURAMET/cg-13/v.01 guideline for testing of dry-blocks

ISO 9001 Manufacturer

Specification Sheet, SS-RTC-158/250

AMETEK continues to develop new techniques to improve performance, accuracy, convenience and functionality of the well-known JOFRA calibration products. By doing so, we maintain our position as the leading worldwide manufacturer of temperature dry-block calibrators.

Advantages of the combined liquid bath/dry-block calibrator

Calibration of many sensors at a time due to more space for example in connection with validation of many thermocouples, which saves time

- Automatic calibration of as many as 24 sensors at a time
- For customers, who only want to use liquid baths
- For calibration of odd sizes and shapes of sensors including sanitary sensors
  WET = no need for inserts, that fit the sensors
  DRY = more space for calibration of special sensors
- Industries who need to calibrate many sensors at a time or short sensors can benefit from the big well
- JOFRACAL software and RTC B-models can handle on-line calibration and documentation of multiple sensors calibrated simultaneously

AMETEK®
TEST & CALIBRATION INSTRUMENTS

FUNCTIONAL SPECIFICATIONS

Temperature range

RTC-158
@ ambient temp. 0°C/32°F ....-37 to 155°C/-35 to 311°F
@ ambient temp. 23°C/73°F ....-22 to 155°C/-8 to 311°F
@ ambient temp. 40°C/104°F .... -9 to 155°C/16 to 311°F
RTC-250
@ ambient temp. 0°C/32°F ....5 to 250°C/41 to 482°F
@ ambient temp. 23°C/73°F ....28 to 250°C/82 to 482°F
@ ambient temp. 40°C/104°F .....45 to 250°C/113 to 482°F

Accuracy (model B & C) with external STS ref. sensor

RTC-158 B & C .... ±0.04°C/±0.07°F
RTC-250 B & C .... ±0.07°C/±0.13°F
12-month period. Relative to reference standard. Specs by use of the external STS-200 reference sensor. Excl. sensor drift.

Accuracy with internal reference sensor

RTC-158 A, B & C.................................. ±0.18°C/±0.32°F
RTC-250 A, B & C.................................. ±0.28°C/±0.50°F

Stability

RTC-158 .... ±0.01°C/±0.018°F
RTC-250 .... ±0.02°C/±0.036°F
Measured after the stability indicator has been on for 15 minutes. Measuring time is 30 minutes.

Radial homogeneity (difference between holes)

RTC-158 @ -22°C/-8°F, Block ....0.03°C/0.05°F
RTC-158 @ 155°C/311°F, Block....................0.05°C/0.09°F
RTC-158 @ range, Bath ....0.015°C/0.03°F
RTC-250 @ range, Block..............................0.05°C/0.09°F
RTC-250 @ range, Bath ....0.015°C/0.03°F

Resolution (user-selectable)

All temperatures ....1° or 0.1° or 0.01° or 0.001°

Heating time

RTC-158 -22 to 23°C/-8 to 73°F.................. 9 minutes
23 to 100°C/73 to 212°F............. 23 minutes
100 to 155°C/212 to 311°F.......... 28 minutes
RTC-250 28 to 100°C/82 to 212°F............... 3 minutes
50 to 100°C/122 to 212°F............. 2 minutes
100 to 250°C/212 to 482°F........... 9 minutes

Cooling time

RTC-158 155 to 100°C/311 to 212°F........... 9 minutes
100 to 23°C/212 to 73°F............. 24 minutes
23 to 0°C/73 to 32°F................... 15 minutes
0 to -15°C/32 to 5°F .... 21 minutes
RTC-250 250 to 100°C/482 to 212°F.......... 27 minutes
100 to 50°C/212 to 122°F........... 27 minutes
50 to 28°C/122 to 82°F............... 28 minutes

Time to stability (approx.)

RTC-158 .... 15 minutes
RTC-250 .... 15 minutes

Immersion depth

RTC-158/250 incl. insulation plug................ 180 mm/7.1 in
RTC-158/250 bath version......................... 150 mm/5.9 in

INPUT SPECIFICATIONS

All input specifications apply to the dry-block of the calibrator running at the respective temperature (stable plus an additional 20 minute period).

All input specifications are valid for RTC-158 and RTC-250.

RTD reference input (B & C models only)

Type.................. 4-wire RTD with true ohm measurements[1)]
F.S. (Full Scale) .... 400 ohm
Accuracy (12 months) ...... ±(0.0012% rdg. + 0.0005% F.S.)

RTD Type	Temperature		12 months	
	°C	°F	°C	°F
Pt100 reference	-22	-8	±0.008	±0.015
	0	32	±0.008	±0.015
	28	82	±0.009	±0.016
	155	311	±0.011	±0.020
	250	482	±0.012	±0.022

Note 1: True ohm measurement is an effective method to eliminate errors from induced thermoelectrical voltage

DLC sensor input (B & C models only)

Type	Temperature		12 months	
	°C	°F	°C	°F
DLC 155	-22	-58	±0.014	±0.025
	0	32	±0.010	±0.018
	28	82	±0.010	±0.018
	155	311	±0.008	±0.015
	250	482	±0.008	±0.015

* at 0.00°C / 0.00°F DLC reading

RTD sensor under test input (B model only)

F.S. (range) .... 400 ohm
Accuracy (12 months)................. ±(0.002% Rdg.+0.002% F.S.)
F.S. (range) .... 4000 ohm
Accuracy (12 months) .... ±(0.005% Rdg. + 0.005% F.S.)
2-wire .... add 50 mOhm

RTD Type	Temperature		12 months	
	°C	°F	°C	°F
Pt100 90(385) IEC	-22	-8	±0.025	±0.045
	0	32	±0.026	±0.047
	28	82	±0.026	±0.047
	155	311	±0.030	±0.054
	250	482	±0.033	±0.060
Pt500 90(385) IEC	-22	-8	±0.113	±0.203
	0	32	±0.116	±0.209
	28	82	±0.118	±0.212
	155	311	±0.129	±0.232
	250	482	±0.131	±0.236
Pt1000 90(385) IEC	-22	-8	±0.063	±0.114
	0	32	±0.064	±0.115
	28	82	±0.066	±0.119
	155	311	±0.075	±0.135
	250	482	±0.082	±0.148

Input and curves for many different resistance sensors such as:

0-400Ω

(P10(90)386/P50(90)385/P100(90)385/P50(90)391/P100(90)391/P100(90)392/M50(90)428/M100(90)428/H120(90)672/Pt-100 MILL)

0-4000Ω

(P200(90)385/P500(90)385/P1000(90)385/YSI-400)

Thermocouple input

Range .... ±78 mV
F.S. (Full Scale) .... 78 mV
Accuracy (12 months) .... ±(0.005% Rdg. + 0.005% F.S.)

TC Type	Temperature		12 months*	
	°C	°F	°C	°F
E	-50	-58	±0.09	±0.17
	0	32	±0.06	±0.11
	155	311	±0.06	±0.11
	320	608	±0.07	±0.13
J	-50	-58	±0.10	±0.18
	0	32	±0.08	±0.14
	155	311	±0.09	±0.16
	320	608	±0.09	±0.16
K	-50	-58	±0.14	±0.24
	0	32	±0.10	±0.19
	155	311	±0.11	±0.20
	320	608	±0.11	±0.20
T	-50	-58	±0.15	±0.26
	0	32	±0.10	±0.18
	155	311	±0.08	±0.15
	320	608	±0.08	±0.15
R	-50	-58	±1.30	±2.35
	0	32	±0.78	±1.40
	155	311	±0.47	±0.84
	320	608	±0.40	±0.72
S	-50	-58	±0.98	±1.76
	0	32	±0.78	±1.40
	155	311	±0.49	±0.89
	320	608	±0.45	±0.81
N	-50	-58	±0.20	±0.35
	0	32	±0.15	±0.27
	155	311	±0.13	±0.23
	320	608	±0.13	±0.24
U	-50	-58	±0.13	±0.24
	0	32	±0.10	±0.18
	155	311	±0.08	±0.14
	320	608	±0.08	±0.15

* Excl. CJC accuracy ±0.3˚C / ±0.54˚F

Transmitter supply

Output voltage.. 24VDC ±10%
Output current....................................... Maximum 28 mA

Transmitter input mA (B model only)

Range .... 0 to 24 mA
Accuracy (12 months) ....±(0.005% Rdg. +0.010% F.S.)

Voltage input VDC (B model only)

Range: .... 0 to 12 VDC
Accuracy (12 months) ....±(0.005% Rdg. +0.010% F.S.)

Switch input (B model only)

Switch dry contacts
Test voltage..Maximum 5 VDC
Test current ....Maximum 2.5 mA

Mains specifications

Voltage ....115V (90-127) / 230V (180-254)
Frequency, non US deliveries ....50 Hz ±5, 60 Hz ±5
Frequency, US deliveries ....60 Hz ±5
Power consumption (max.), RTC-158......................400 W
Power consumption (max.), RTC-250....................1150 W

Communication interface

Serial data interface ....USB 2.0 device port
Serial data interface ....USB 2.0 host double port*
LAN.................................. Ethernet MAC 10/100 Base-T*
SD.. SD slot*
* for future expansion

Miscellaneous

Operating ambient temperature........0 to 40°C/32 to 104°F
Storage temperature .... -20 to 50˚C/-4 to 122˚F
Humidity .... 0 to 90% RH
Protection class IP-10

PHYSICAL SPECIFICATIONS

Weight and instrument size (L x W x H)

RTC-158 .... 11 kg/24.3 lb
RTC-250 ....9.9 kg/ 21.8 lb
RTC-158/250.... 366 x 171 x 363 mm / 14.4 x 6.7 x 14.3 in

Shipping (without carrying case)

RTC-158 .... 17 kg/37.5 lb
RTC-250 .... 16 kg/35.3 lb
Size.....................580 x 250 x 500 mm/22.8 x 9.8 x 19.7 in

Shipping (including optional carrying case)

RTC-158 .... 28 kg/61.7 lb
RTC-250 .... 27 kg/59.6 lb
Size...................550 x 430 x 660 mm/21.7 x 16.9 x 26.0 in

INSERTS

Insert dimensions

RTC-158/250 outer diameter ....63.5 mm/2.5 in
RTC-158/250 length......................................160 mm/6.3 in

Weight of non-drilled insert (approx.)

RTC-158/250...1200 g/42.3 oz

Alloy

RTC-158/250................................ Special aluminium alloy

Use of other inserts may reduce performance of the calibrator. To get the best results out of the calibrator, the insert dimensions, tolerance and material is critical. We highly advise using JOFRA inserts, as they guarantee trouble free operation.

A.2 Calibrator Certificate of Calibration

ilac-MRA DANAK CAL Reg.No. 494

AMETEK TEST & CALIBRATION INSTRUMENTS

Certificate of Calibration

Metrology Calibration laboratory

Certificate no.: E 43552

Device under test

Description:	PT100 Resistance probe		
Serial number:	**592793-05**	Model:	STS-200 A 916
Manufacturer:	AMETEK Denmark A/S		
Range:	-37°C to 155°C-34,6°F to 311°F		
Laboratory subject no:	**SA 27377**	**S 24097**	
Date of system calibration:	**jun 1 2017**		

System calibration with:

Description:	Reference Temperature Calibrator	Model:	RTC-158-B
Manufacturer:	AMETEK Denmark A/S		
Serial number:	596562-00038		

Customer information

Client:	Technische Universität Berlin	Number:	--
Address:	Marchstraße 18 10587 Berlin	Phone:	--

Remarks

As found calibration.
The calibration was carried out with both the laboratory reference sensor and the external STS sensor immersed 140 mm into the calibration insert for each temperature point. Standard insulation plug was mounted and present during the calibration.
The insert hole where the reference probe was immersed, is equal to the probe diameter + 0,2 mm.
Contribution to reported combined uncertainties arises from unit stability and reference equipment including possible correction from immersion depth.

Calibrated by:

Ole Asklund Jørgensen
Calibration technician

Approved by:

Ole A. Jørgensen
Digitalt signeret af Ole A. Jørgensen
Dato: 2017.06.02 10:39:02 +02'00'

A summery of this report may be issued only when it is clearly stated that it is a summary and only if the full report is cacheable to the public, or if the summary has been approved by AMETEK Denmark A/S, Metrology Laboratory.

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Certificate of Calibration

Metrology Calibration laboratory

Certificate no.: E 43552

Calibration conditions

Calibration procedure:	126563		
Ambient temperature:	23 ±2 °C	Reference id.:	Y007
Relative humidity:	30..85%	Reference id.:	Y007

Reference equipment applied

Description:	Manufacturer:	Model:	Id. number:
Reference sensor	Rosemount	CE162	T021
Resistance Bridge	AMETEK Denmark A/S	DTI 1000 B	E159
Calibration Insert	AMETEK Denmark A/S	127877	in075
Gradient Sensors	AMETEK Denmark A/S		T173 - T174
Resistance Bridge	AMETEK Denmark A/S	DTI 1000 A	E052

Set °C	Actual °C	Measured °C	Deviation °C	Uncertainty °C	Specification °C
-22,0	-21,937	-21,928	0,009	±0,020	±0,04
-15,0	-14,942	-14,932	0,010	±0,020	±0,04
0,0	0,042	0,051	0,009	±0,020	±0,04
25,0	25,020	25,030	0,010	±0,020	±0,04
50,0	50,003	50,015	0,012	±0,020	±0,04
75,0	74,986	74,999	0,013	±0,020	±0,04
100,0	99,963	99,976	0,013	±0,020	±0,04
125,0	124,940	124,954	0,014	±0,020	±0,04
155,0	154,936	154,950	0,014	±0,020	±0,04

The stated uncertainty is based on the entire set-up including object under test.

The reported uncertainty is based upon a standard uncertainty multiplied by a coverage factor k=2, providing a level of confidence of approximate 95%. The uncertainty evaluation has been carried out in accordance with DANAK requirements.
The uncertainty is calculated following EA-4/02

Calibration coefficients
The calibration coefficients as defined in ITS-90, are as follows:

For the range:

-22 to 155 °C

R(0,01°C):		100,081970 Ω
Values below 0°C	aLR:	-1,993622E-02
	bLR:	1,903192E-03
Values above 0°C	aHR:	-2,011073E-02
	bHR:	-1,007986E-04

The calibration coefficients stated in this certificate is valid when the device under test is used as part of the system described in this certificate.

These may be different from the calibration coefficients stated on the certificate for the device under test as an individual device.

If the device under test is used as an individual or in combination with other instruments than described in this certificate, the calibration coefficients from the certificate for the device under test as an individual must be used.

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Certificate of Calibration

Metrology Calibration laboratory

Certificate no.: E 43552

DANAK

DANAK is the national accreditation body in Denmark in compliance with EU regulation No. 765/2008

DANAK participates in the multilateral agreements for testing and calibration under European co-operation for Accreditation (EA) and under International Laboratorie Accreditation Cooperation (ILAC) based on peerevaluation. Accredited test reports and calibration certificates issued by laboratories accredited by DANAK are recognized cross border by members of EA and ILAC equal to test reports and calibration certificates issued by these members' accredited laboratories.

The use of the accreditation mark on test reports and calibration certificates or reference to accreditation, documents that the service is provided as an accredited service under the company's DANAK accreditation.

The calibration certificate is covered by DANAK accreditation and the multilateral agreements from EA and ILAC for calibration which ensures that measurements are traceable to the international system of units, SI.

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TEST & CALIBRATION INSTRUMENTS

Certificate of Calibration

Metrology Calibration laboratory

Certificate no.: E 43553

Device under test

Description: Reference Temperature Calibrator
Serial number: **596562-00038** Model: RTC-158-B
Manufacturer: AMETEK Denmark A/S
Range: -22 to 155 °C/-13 to 311 °F
Laboratory subject no: **SA 29143** **S 24097**
Date of calibration: **jun 1 2017**

Customer information

Client:	Technische Universität Berlin	Number:	- -
Address:	Marchstraße 18 10587 Berlin	Phone:	- -

Remarks

Calibration as found. The calibration was carried out with the laboratory reference sensor immersed 140 mm into the calibration insert for each temperature point. Standard insulation plug was mounted and present during the calibration.
The insert hole where the reference probe was immersed, is equal to the probe diameter + 0,2 mm.
Contribution to reported combined uncertainties arises from unit stability and reference equipment including possible correction from immersion depth.

Calibrated by:

Ole Asklund Jørgensen
Calibration technician

Approved by:

Ole A. Jørgensen Digitalt signeret af Ole A. Jørgensen
Dato: 2017.06.02 10:37:14 +02'00'

A summery of this report may be issued only when it is clearly stated that it is a summary and only if the full report is cacheable to the public, or if the summary has been approved by AMETEK Denmark A/S, Metrology Laboratory.

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ilac-MRA DANAK CAL Reg.No. 494

AMETEK® TEST & CALIBRATION INSTRUMENTS

Certificate of Calibration

Metrology Calibration laboratory

Certificate no.: E 43553

Calibration conditions

Calibration procedure:	126553		
Ambient temperature:	23 ±2 °C	Reference id.:	Y007
Relative humidity:	30..85%	Reference id.:	Y007

Reference equipment applied

Description:	Manufacturer:	Model:	Id. number:
Reference sensor	Rosemount	162 CE	T021
Resistance Bridge	AMETEK Denmark A/S	DTI1000 B	E159
Gradient Sensors	AMETEK Denmark A/S	127356	T173 -T174
Resistance Bridge	AMETEK Denmark A/S	DTI1000 A	E052
Insert	AMETEK Denmark A/S	127877	in075

Set value		Read value		True value		Deviation		Uncertainty	
°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
-22,0	-7,6	-22,000	-7,600	-21,937	-7,487	-0,063	-0,113	±0,020	±0,036
-15,0	5,0	-15,000	5,000	-14,944	5,101	-0,056	-0,101	±0,020	±0,036
0,0	32,0	0,000	32,000	0,041	32,074	-0,041	-0,074	±0,020	±0,036
25,0	77,0	25,000	77,000	25,016	77,029	-0,016	-0,029	±0,020	±0,036
50,0	122,0	50,000	122,000	50,002	122,004	-0,002	-0,004	±0,020	±0,036
75,0	167,0	75,000	167,000	74,986	166,975	0,014	0,025	±0,020	±0,036
100,0	212,0	100,000	212,000	99,961	211,930	0,039	0,070	±0,020	±0,036
125,0	257,0	125,000	257,000	124,937	256,887	0,063	0,113	±0,020	±0,036
155,0	311,0	155,000	311,000	154,933	310,879	0,067	0,121	±0,020	±0,036
155,0	311,0							±0,000	±0,000

The stated uncertainty is based on the entire set-up including object under test.

The reported uncertainty is based upon a standard uncertainty multiplied by a coverage factor k=2, providing a level of confidence of approximate 95%. The uncertainty evaluation has been carried out in accordance with DANAK requirements.
The uncertainty is calculated following EA-4/02

DANAK

DANAK is the national accreditation body in Denmark in compliance with EU regulation No. 765/2008

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The use of the accreditation mark on test reports and calibration certificates or reference to accreditation, documents that the service is provided as an accredited service under the company's DANAK accreditation.

The calibration certificate is covered by DANAK accreditation and the multilateral agreements from EA and ILAC for calibration which ensures that measurements are traceable to the international system of units, SI.

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B Digital Annex

B.1 Description of the Python Calibration Script

Description of the python code used to calibrate the temperature sensors. Whole process described in section 2.2 .

8pt5pt5pt8pt8pt

```
@author: Lukas

@modified: Toni

#%% Library Import

import matplotlib.pyplot as plt
import SteadyState_Calc as SSC
import h5py
import numpy as np
import pandas as pd



#%% Data import. Two data files, as the calibration was performed
#%% through  two different days, one file per day.

Path = '../../messdaten/File/YYYYMMDD_HH_MM_SS_Messungen/sease_m.h5'
Path2 = '../../messdaten/File/YYYYMMDD_HH_MM_SS_Messungen/sease_m.h5'


#%% Read in data, time and 3 different sensors.
#%% For the data of the first day.

with h5py.File(Path,'r') as hf:
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor_time')
time = np.array(data)
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor1')
VNP = np.array(data)
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor2')
VNP2 = np.array(data)
```

```
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor3')
VNP3 = np.array(data)

#%% Produce Pandas dataframe

df = pd.DataFrame()

#%% Rewriting in a pandas series, put together the sensor values and
#%% time of the measurements

serie = pd.Series(VNP[:,0], pd.to_datetime('1904-01-01') +
 pd.to_timedelta(time[:,0]+ 2*3600, 's'), name = 'VNP')

#%% Rewrite into a pandas dataframe

df = pd.concat([df,serie], axis = 1)

#%% The same for the other data

serie = pd.Series(VNP2[:,0], pd.to_datetime('1904-01-01') +
 pd.to_timedelta(time[:,0]+ 2*3600, 's'), name = 'VNP2')

df = pd.concat([df,serie], axis = 1)

serie = pd.Series(VNP3[:,0], pd.to_datetime('1904-01-01') +
 pd.to_timedelta(time[:,0]+ 2*3600, 's'), name = 'VNP3')

df = pd.concat([df,serie], axis = 1)

#%% Read in data obtained from the calibrator


PathRef = '../../messdatenKaliJune2016/File/
_CalibrationFAKS_YY-MM-DD__HHMMSS.txt'

Reference = pd.read_csv(PathRef, sep='\t', parse_dates=[0],
 index_col=0)

#%% Delete the internal sensor of the calibrator, only the reference
#%%  sensor is needed. The calibrator has two sensors in it, one used as
#%%  a reference sensor with respect to which the other sensors are
#%%  calibrated, and an internal sensor to control the temperature of
#%%  the device.
```

```
Reference = Reference.loc[:,['Reference Sensor']]

#%% Read in data of the second day of calibration

df2 = pd.DataFrame()

#%% Repeat the same proces as followed for the first data file
#%%  of the sensors

with h5py.File(Path2,'r') as hf:
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor_time')
time = np.array(data)
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor1')
VNP = np.array(data)
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor2')
VNP2 = np.array(data)
data = hf.get('YYYY-MM-DD_HH:MM:SS/Sensor3')
VNP3 = np.array(data)

serie = pd.Series(VNP[:,0], pd.to_datetime('1904-01-01') +
 pd.to_timedelta(time[:,0]+ 2*3600, 's'), name = 'VNP')

df2 = pd.concat([df2,serie], axis = 1)

serie = pd.Series(VNP2[:,0], pd.to_datetime('1904-01-01') +
 pd.to_timedelta(time[:,0]+ 2*3600, 's'), name = 'VNP2')

df2 = pd.concat([df2,serie], axis = 1)

serie = pd.Series(VNP3[:,0], pd.to_datetime('1904-01-01') +
 pd.to_timedelta(time[:,0]+ 2*3600, 's'), name = 'VNP3')

df2 = pd.concat([df2,serie], axis = 1)


#%% Put together the two data frames corresponding to the
#%% two days of calibration

dftot = pd.concat([df,df2])


#%% Summarize in dict. Selection of the interval of interest,
```

```
#%% where the calibration was performed. The data outside this time
#%% interval is not interesting for the calculation

data_dict = {'ein_name':dftot['YYYY-MM-DD HH:MM':'YYYY-MM-DD HH:MM'],
 'ein weiter Name':Reference['YYYY-MM-DD HH:MM':'YYYY-MM-DD HH:MM']}

#%% Read the parameters of the calibration function

df_SSPar = pd.read_csv('SSPara_Beispiel.csv', index_col = 'Parameter')

#%% Find the steady-states using the SteadyStateCalculation function.
#%% Linear approximation.

SSt = SSC.SteadyStateCalculation(data_dict, df_SSPar)
SSt.run_checks()

#%% Empty the plot

plt.clf()

#%% Plot all data
for sensor_gruppe in data_dict.keys():
plt.plot(data_dict[sensor_gruppe])

#%% Show Steady-states

e = SSt.steadyStates
for i in range(SSt.anz_SSteadyStates):

plt.plot(data_dict[sensor_gruppe][e.loc[i,'all_sensorsbegin']:
 e.loc[i,'all_sensorsend']], 'go', markersize=3)

plt.show()



#%% Desired results, the name of the reference sensor and the
#%% degree of the polynomial are passed as arguments

kal_data = SSt.calibrate('Reference Sensor',1)

#%% kal_data is a dataframe which gives the linear approximation
#%% parameters x1 and x0 that correct the not calibrated values for
```

#%% the temperature sensor. It also gives the covariance matrix.